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This paper presents results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

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Lunar Surface and Subsurface Magnetic Susceptibility Instrumentation*

EDGAR M. BOLLIN†

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Summary—**Multicoil induction measurements of the lunar surface and subsurface magnetic susceptibility are under study. Major considerations are the improvement of the accuracy and logging ability of various probe configurations. Special boundary conditions of high vacuum, extreme ambient temperature variation, restriction to mechanically passive systems, simple electronics, low power and light weight all contribute to degradation of the accuracy of the instrument.**

Measurements in the range of 10 to 100,000 micro-oersted/gauss are of interest. Nonsedimentary rocks range from 40 to 1000 μ-oersted/gauss and the presence of nickel-iron meteoritic material may extend the range beyond the present limits of measurement. The determination of the presence or absence of meteoritic material is necessary to validate not only the accuracy of the susceptibility measurement, but also the accuracy of low level magnetometer measurements.

INTRODUCTION

A GROUP OF geophysical parameter instruments have been studied to determine the feasibility of making lunar surface and subsurface measurements. In both surface and subsurface magnetic susceptibility instruments the experiment employs an air core transformer in which the change in mutual inductance between the primary and secondary is measured in vacuum and after emplacement. Corrections to the measured change in inductance are made by measuring

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the temperature of the coils at the time of measurement.

Surface instrumentation is an individual transducer which can be designed to optimize conditions of measurement through proper spacecraft deployment and transducer size and configuration. The accuracy of the measurement is subject to basic transducer accuracy and the topography and continuity of the surface. Stereoscopic television coverage of the measurement will allow a reproduction of the surface to minimize these errors.

The subsurface instrument is integrated into a down-hole logging sonde which introduces the additional requirements of compatibility or interaction with other instruments, internal wiring, and the physical configuration of the exterior of the sonde. The magnetic susceptibility instrument has been integrated with density, acoustic velocity, infrared interferometer-spectrometer radiation temperature, contact temperature, thermal diffusivity, and hole-size caliper. In most cases, the surface presented to the down-hole sonde will be more uniform than that for the surface instruments and temperature variations will be less extreme. Errors introduced by bore-hole variation in poorly consolidated material will be corrected by measurement of the diameter of the hole.

Scientific Objectives of Measurement

It is desirable to include the range from 10 to 1000 μ cgs units to indicate whether or not the surface and subsurface have the same relative magnitude as non-sedimentary rocks on earth. If such is not the case, it is extremely desirable to ascertain the magnitude of the discrepancy.

The range from 1000 to 100,000 μ cgs units is of considerable interest in view of the large percentage of iron (0.1 to 90 per cent) in particles below 30 microns collected at altitudes above 40,000 feet (Fireman and Kistner[1]). Relatively undisturbed surface measurements would tend to indicate if particles in deep space were of a similar nature. This upper range of susceptibilities, with accompanying indication of conductivity will give evidence of the presence or absence of typical nickel-iron meteoritic material.

Regardless of the range encountered, the relative changes in magnetic susceptibility with depth below the surface will be a most important measurement. The changes in susceptibility will be the only measurement which will give an indication of the magnitude of, and the presence or absence of small or abrupt changes in the structural layering of the subsurface.

The expected very low magnetic field of the moon will make it absolutely necessary to make a measurement of magnetic susceptibility of the surface and subsurface if magnetometer measurements are to be meaningful. Otherwise, the magnetometer may measure the field of a random nickel-iron meteorite without any indication of its presence.

Problems Associated with Spacecraft Measurement

There is a multitude of restrictions associated with spacecraft measurement that, in a large part, control the design of the transducer and associated electronics as closely as the scientific requirements of the experiment. These restrictions are in many cases interrelated to such a degree that they are mutually exclusive of many normally accepted techniques in the laboratory or even field measurements. Almost none of the facets of spacecraft measurement are conductive to increased accuracy over normal laboratory procedures, with the possible exception of the availability of larger than normal concentration of manpower, funds, and data reduction facilities.

A few of the restrictions imposed by lunar spacecraft measurement are 1) vacuum above 10^{-9} Torr, 2) ambient temperature variation from 100° to 400°K, 3) mechanically simple or passive manipulation capabilities, 4) low power and low weight, 5) restricted dynamic range, 6) restricted amplitude accuracy and frequency response of transmission systems, 7) relatively inaccurate temperature measuring facilities, 8) in general, only passive temperature control of the transducer, 9) limited temperature control of electronic storage facilities, 10) no temperature control of electrical leads from transducer to electronics, and 11) very little or no control over the condition of the sample which is to furnish the measured quantity.

While some of these restrictions or requirements are not as severe as to prevent measurement, almost all degrade accuracy to an extent that is intolerable when compared with normal philosophy concerning precision laboratory measurement. Restrictions on the required accuracy of the measurment must be completely revised in the light of what can or cannot be accomplished and still obtain useful and meaningful information. However, excessive degradation of acceptable accuracy cannot be tolerated.

Description of Method

The measurement of magnetic susceptibility by the induction method is essentially a receiver coil which has its induced field nulled to zero by two equal series-opposing transmitter coils in the absence of a sample. The reverse configuration of one transmitter coil and two equal series-opposing receiver coils may be used as well. The balanced signal at the receiver coil or coils is distorted by the introduction of a magnetic material into one of the receiver coils or in the area between one of the transmitter coils and the receiver coil. In either case, the distortion of the field causes a change in the mutual inductance of the originally balanced condition. This change in mutual inductance is proportional to the magnetic susceptibility of the sample. The physical arrangement may be either coaxial planar (flat sample) or coaxial linear (cylindrical or tubular sample).

[1] E. L. Fireman and G. A. Kistner, "The nature of dust collected at high altitudes," *Geochim. et Cosmochim. Acta*, vol. 24, pp. 10–22; June, 1961.

In the absence of a sample zero transducer, output may be obtained by nulling the output to zero by either a bridge arrangement or by the electromechanical arrangement of the coils themselves. If a bridge arrangement is used, two alternatives for output sensing are possible. In one case, observation may be made of the magnitude of the change of the associated bridge components, or in the other case, observation may be made of the magnitude of the deviation of the output signal from the null condition. Due to the complexity of automatically balancing both in-phase and quadrature voltages with the first method, the second method is to be desired for spacecraft use.

A further simplification is possible. All bridge components exclusive of the transducer coils are removed and "transformer interaction" of the output from the transducer coils is measured. This removes the possibility of the temperature sensitivity of the bridge components and a reduction of the effect of the spurious harmonic content of the output signal. Thus the stability of the null voltage, under wide excursions of ambient temperature, is mainly dependent upon the electromechanical stability of the transducer coil system.

Development of Transducers

A feasibility study of the development of the magnetic susceptibility instrumentation was undertaken by the Exploration and Research Division of Texaco, Inc., under a NASA 7-100 work contract. The surface instrumentation developed was essentially an unmodified design by H. M. Mooney,[2,3] consisting of a coaxial-planar arrangement of the transducer coils. The subsurface coil configuration was redesigned in a coaxial-linear configuration. A single transmitter coil and two series-aiding receiver coils were used. An external pair of bucking coils were used to reduce the output to a nominal zero with a sample absent. These two designs and the bridge configuration are shown in Fig. 1.

A refinement of the design of the surface instrument was carried out by a computer evaluation of the relative size of the coils and their spacing to achieve a minimization of the variation in the output with variable height above the surface to be measured. In the original design, the upper transmitter coil and the receiver coil were the same size. The measured change in mutual inductance is mainly due to the distortion of the field between the lower transmitter coil and the receiver coil. By decreasing the spacing of the upper transmitter coil from the co-planar pair and increasing its diameter, the field between the upper transmitter coil and the receiver coil was also distorted as the surface was approached. This interaction resulted in a negative signal contribution from this pair. By critically adjusting the diameter and the spacing of the upper transmitter coil, it is thus possible to achieve a broad flat maxima at some height above the surface. This height represents the measuring position which is the least sensitive to variations in height and minor surface variations in topography.

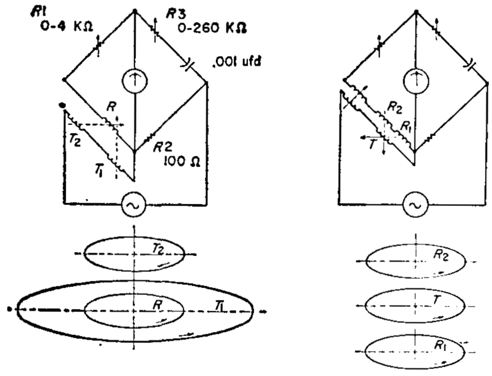

Fig. 1—Developmental configurations. (a) Surface. (b) Subsurface.

Further development of the system was performed by Texaco Experiment Inc., under a NASA 7-100 contract (Canup, *et al.*)[4] The balanced bridge approach was abandoned due to incompatibility with spacecraft systems, and the size of the surface coils was reduced from twelve to four inches to reduce spacecraft manipulation requirements. Available voltage was set at 5 v-rms at a frequency of 3800 cps to conserve weight and power of the spacecraft generator system.

Surface Unit

A comparison of the direct output voltage was conducted with the arrangement shown in Fig. 2. The input voltage was 25 v-rms at 1000 cps as used for the original model. A comparison of the results is shown in Fig. 3. The major difference in the two curves is that the linear portion of the curve is extended by the direct measurement technique.

A comparison was made of the system with variable voltage and frequency. The data are shown in Fig. 4. The output voltage decreases as the ratio of the input decreases, and increasing the frequency to 5000 cps causes a slight nonlinearity as a result of eddy current losses in the iron particles used for relative calibration purposes.

Drift of the null point with temperature variation was found to be due to variable coefficients of expansion according to the direction of the fibers in the epoxy fiberglass used for the coil forms. It was found that by proper choice of dimensions and points of attachment of the coil forms on the support rod that the expansions could be made to counteract each other, and the resultant null drift could be minimized.

To determine the feasibility of conductivity measurements with the system, measurements were made with 40 mesh iron filings mixed with sand and with boiler

[2] H. M. Mooney, "Magnetic susceptibility measurements in Minnesota, Technique of Measurement," *Geophysics*, vol. 17, pp. 531–543; July, 1952.

[3] H. M. Mooney, "Magnetics in geology," *Electronics*, vol. 26, pp. 143–145; October, 1953.

[4] R. E. Canup, *et al.*, "Surveyor Geophysical International," Texaco Experiment, Inc., Richmond, Va., Interim Rept. No. TP-192; 1962.

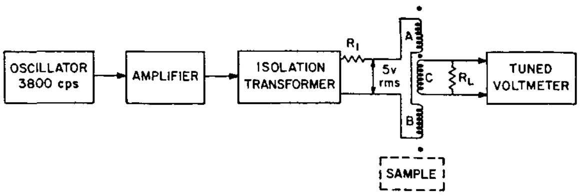

Fig. 2—System block diagram of the surface magnetic susceptibility instrument.

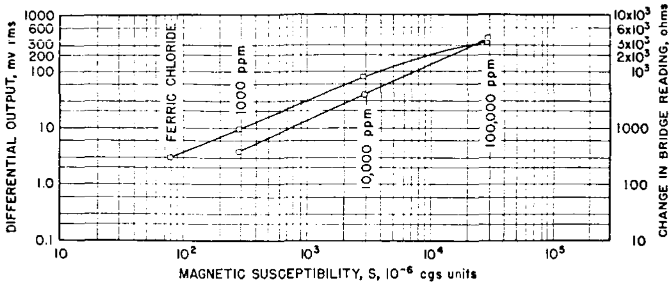

Fig. 3—Comparison of responses of direct voltage measurement with bridge-balance method.

○ Direct voltage measurement □ Bridge-balance method
Input, 25 v rms at 1000 cps.

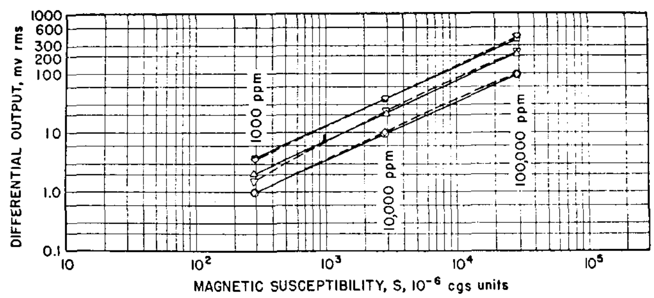

Fig. 4—Comparison of instrument response with input voltage.

□ 25 v rms, 1000 cps	▽ 25 v rms, 1000 cps
△ 12.7 v rms, 1000 cps	▽ 12.7 v rms, 5000 cps
○ 5 v rms, 1000 cps.	◇ 5 v rms, 5000 cps

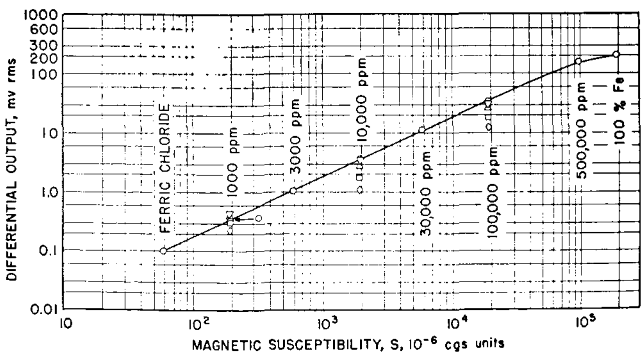

Fig. 5—Response for even and uneven surfaces.

○ Even surfaces	□ Uneven surfaces, 30°
▽ Uneven surfaces, 0°	◇ Uneven surfaces, 45°
△ Uneven surfaces, 15°	

Average of nulls in air, 1.5 mv.

plate iron. Although the output was saturated by 100 per cent iron filings, the phase angle was measurable and varied according to the conductivity of the material. The phase angle varied from 5° with 100 per cent iron filings to 66.4° with iron boiler plate.

The accuracy of the surface system is shown in Fig. 5. It is observable that the curve for even surfaces is linear from 59.2 μ cgs units to approximately 500,000 μ cgs units and becomes only moderately nonlinear up to the point where 100 per cent iron filings were present in the calibration material. Repeatability of the voltage measurements was found to be within ±5 per cent of the average.

Subsurface Unit

The subsurface unit has undergone very little modification from the original design. The restrictions of size and operational requirements of the down-hole sonde do not allow a readily apparent solution to coil configuration as with the surface unit. A normal symmetrical balance arrangement cannot be used because the reference half of the pair cannot be spatially removed from the influence of the sample. A separate set of bucking coils housed in the spacecraft electronics has been designed to null the output in the absence of a sample. However, self-compensating expansion characteristics with the two coil systems at different temperatures is not possible and null drift is extreme.

A further requirement on the subsurface instrument is the ability to discern sharp discontinuities in the media. The determination of the presence or absence of a discontinuous structure must be observed with the magnetic susceptibility instrument as the other instruments are not suited to this type of function. The original design of the instrumentation does not result in a single response for a small discontinuity, and a double maxima occurs when traversed through a thin area of high susceptibility. Since the two receiver coils are connected in a series-aiding arrangement, there is no logical reason for the presence of more than one receiver coil. In this respect, the present instrument is unsuitable. A separate nulling assembly which may have very large temperature differences from the transducer is also considered to be unsatisfactory.

A series of coil configurations are being experimentally examined at the Jet Propulsion Laboratory to determine an optimum arrangement. The design objectives are 1) a single high resolution response to changes in a horizon of only a few millimeters, 2) all coils contained within a small region of the sonde, 3) self-compensating characteristics for temperature variation, 4) increased sensitivity over the original design, and 5) a minimization of the change in calibration with bore-hole size variation.

Two arrangements seem to show some promise. One is three coils with their axes at right angles to the axis of the sonde. The two transmitter coils are wound series-opposing, displaced above and below the receiver coil [Fig. 6(a)]. The second arrangement, shown in Fig. 6(b),

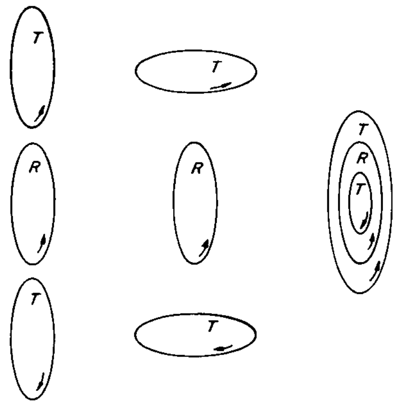

Fig. 6—Experimental subsurface configurations. (a) Coplanar Vertical. (b) Axial normal. (c) Coplanar coaxial.

has the two transmitter coils wound series-opposing above and below the receiver coil with their axes parallel to the axis of the sonde. The receiver coil has its axis at right angles to the axis of the transmitter coils and the sonde to provide a minimum signal without a sample present. This latter configuration is especially insensitive to movement of the coils for distances of up to $\frac{1}{4}$ inch without appreciable null drift. Both coil configurations have not been tested completely, however, preliminary measurements show at least an order-of-magnitude improvement over previous designs.

A third arrangement, Fig. 6(c), is to be tested in which there are three coaxial-coplanar coils with their axes at right angles to the axis of the sonde. The inner coil is a transmitter coil of relatively few turns directly overlain by the receiver coil with very tight coupling to minimize external interaction. The second transmitter coil is of a relatively large number of turns to achieve a balance with the inner transmitter coil. The diameter of the outer transmitter coil is of maximum diameter allowable with probe dimensions to have minimum coupling with the receiver coil. The ratio of turns of the two transmitter coils are adjusted to compensate for the coupling differences.

Summary

An instrumental configuration has been designed that will allow the collection of useful and meaningful information about the magnetic susceptibility of the lunar surface. The designs of the transducers and the spacecraft electronics are not considered to be completely optimized as yet and experimental work is now in progress.

It is evident that an optimum configuration for the down-hole sonde has not been realized and cannot be decided without testing all of the requirements set upon the operation of the sonde. However, the outlook is optimistic that the conflicting requirements of the down-hole sonde will be satisfied.